Alexandria Engineering Journal (2013) 52, 627–636

Alexandria University

Alexandria Engineering Journal

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ORIGINAL ARTICLE

Parametric analysis of a cabin fire using a zone fire model

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Received 18 August 2011; revised 10 August 2013; accepted 10 October 2013
Available online 01 November 2013

KEYWORDS

Fire safety;
Zone models;
Ro-ro/passenger ships;
Fractional effective doses

Abstract Fire onboard has always been considered as one of the most relevant hazards to ships. As an effect of ship fires, toxic smoke might develop and start spreading from the compartment of fire origin to other connected compartments. Such smoke can cause injuries and deaths and can impair the passengers and crew's abilities to muster and evacuate the ship on time. Fire simulation models have been developed and are continuously being refined and validated to estimate the consequences of compartment fires. The available fire models generally include the capability to evaluate fire development and smoke movement as well as the time to reach critical untenable conditions inside such compartments. The work presented in this paper shows the results of a parametric study using the latest version of one of the available fire models of the zone model type, called BRANZFIRE, in order to assess the effect of changing the size of the compartments on the time available for occupants to escape safely.

1. Introduction

The majority of fatal and non-fatal casualties from fires result from exposure to toxic smoke, but there can be considerable differences between different types of fires in terms of the smoke composition and the ways in which it affects people. Passenger ship's occupants may be many hours or days from shore, so that any fire that develops rapidly and makes a way into the accommodation spaces is likely to be lethal due to asphyxiation of occupants.

Fortunately, such occurrences are rare. But if it happened, it may results in contamination of the atmosphere of the compartment with low-concentration of toxic gases that may have to be tolerated for a number of hours. In such situations the major concerns must be initially the psychological and physiological effects on passengers and crew of exposure to an irritant and optically obscure smoke, and then the asphyxiation hazards presented by lung inflammation and gradual intoxication by asphyxiant gases such as carbon monoxide, both of which may result in long-term respiratory tract and neural damage in survivors [1].

When evaluating the consequences of heat and fire effluents to human life, the crucial criterion for life safety in fires is that, the available safe egress time to be greater than the required safe egress time. The available safe egress time is the interval between the time of ignition and the time after

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Peer review under responsibility of Faculty of Engineering, Alexandria University.

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http://dx.doi.org/10.1016/j.aej.2013.10.001

Nomenclature

C_{soot}	mass concentration of soot in the upper layer (kg)
%COHb	percentage concentration of carboxy-haemoglobin
$\%CO_2$	percentage concentration of carbon dioxide
$\%O_2$	percentage concentration of oxygen
FED	fractional effective dose
FED_{CO}	fractional effective dose for carbon monoxide
FED_{O2}	fractional effective dose for oxygen hypoxia
FED_{rad}	fractional effective dose for thermal radiation
FED_{tot}	total fraction effective dose
k_{avg}	average extinction coefficient (m^{-1})
k_m	specific extinction coefficient (m^2/kg soot)
ppmCO	concentration of carbon monoxide as part per million
$\dot{q}_{rad}$	incident radiation (W/m^2)
RMV	volume (in litres) of air breathed per minute
t	time step (min)
T_u	upper layer temperature (K)
V	visibility (m)
Y_{soot}	soot yield
ε_u	upper layer emissivity
ϕ	configuration factor between layer interface and target
σ	Stefan–Boltzmann constant ($W/m^2\,K^4$)
ρ_u	upper layer density (kg/m^3)

which conditions become untenable such that occupants can no longer take effective action to accomplish their own escape.

The required safe egress time is the time required for occupants to travel from their location at the time of ignition to a place of safe refuge. As occupants are exposed to heat and fire effluents, their escape behaviour, movement speed, and choice of escape route are also affected, reducing the efficiency of their actions and delaying escape. All of these factors affect the time required for escape.

The available safe egress time depends on many characteristics of the fire, the compartment, and the occupants themselves. The nature of both the fire (e.g., HRR, quantity and types of combustibles, fuel chemistry) and the compartment (e.g., dimensions, ventilation) determines the toxic gas concentrations, the gas and surface temperatures, and the density of smoke throughout the compartment as a function of time. The characteristics of the occupants (e.g., age, state of health, location relative to the fire, activity at the time of exposure) also affect the impact of their exposure to the heat and smoke. Moreover, estimation of exposure is determined in part by assumptions regarding the position of the occupants' heads (noses) relative to the hot smoke layer that forms near ceilings and descends as the fire grows. As a result of all these factors, each occupant will likely have a different estimated available safe egress time [2].

There are different methods (e.g., computer fire modelling programs, hand calculation models), which enable estimation of the status of exposed occupants at specified time intervals throughout the development of a fire scenario, up to the time at which such exposure may prevent occupants from taking effective action to accomplish their own escape. Comparison of this time with the time required for occupants to escape safely to a place of safe refuge serves to evaluate the effectiveness of a structure's fire safety design. If such comparison reveals insufficient available safe egress time, a variety of protection strategies will then need to be considered by the designer of that structure.

There are two types of computer fire models available to the community of fire protection engineers and to the research arena, namely, zone models and field models. Among the 56 zone fire models, declared in Salem [3], there are only two models, which are commonly in use in many practical applications. This is due to their abilities to deal with multi-connected compartments, their availability to everyone and their continuous update. These zone models are CFAST and BRANZFIRE.

A series of comprehensive comparisons between three existing zone fire models, namely CFAST, BRANZFIRE and Räume, and a benchmark field model called FDS, involving typical ship layouts, have been carried out in Salem [4]. The most important findings of these comparisons are that there is no zone fire model which is useful for all applications, and also that some of the available zone models have some deficiencies in their sub-models that make them incapable of predicting some of the important parameters identified.

The objective of the current work is to study the process of using a computer fire simulation program to evaluate the effects of changing the main dimensions of the compartments of certain design fire scenario, which is probable to take place onboard ro-ro/passenger ships, on the output parameters related to the potential fire hazard (i.e., the available safe egress time). The author selected BRANZFIRE 2012.1 [5–8], which is the latest version, to carry out this analysis. The reason for selecting BRANZFIRE is that the model has been tested by the author with another zone model against available experimental results [9]. The outcome of this test was that BRANZFIRE has showed reasonable agreement with the experimental results and it is found suitable for conducting the current study.

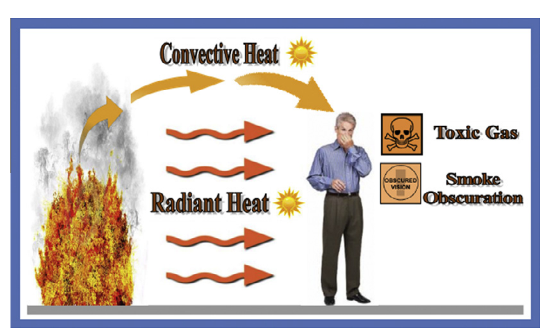

Figure 1 Different hazards of smoke and heat to occupants.

2. Hazards due to fire

Hazards due to fire depend on the elements at risk. These elements may include people (passengers and crew), property (ship and/or her equipments) and the global environment. Hazards to people consist of the following:

1. Inhalation of asphyxiant gases.
2. Exposure to radiant and convective heats.
3. Exposure to sensory/upper respiratory irritants.
4. Visual obscuration due to smoke.

Fig. 1 shows different hazards of smoke and heat from compartment fires to its occupants.

Hazards to property may be thermal destruction, fouling or corrosivity. Hazards to the global environment may be considered as chemical or thermal pollution effects. The tolerance to each hazard must be quantitatively known and assessed against appropriate measures from fire tests [10]. This study is concerned only with the fire hazards associated with people.

3. How BRANZFIRE solves the smoke toxicity problem?

BRANZFIRE is a zone model including flame spread options on walls and ceilings and is used to calculate the time-dependent distribution of smoke, fire gases and heat throughout a collection of connected compartments during a fire. In BRANZFIRE, each compartment is divided into two layers, an upper hot layer and a cold lower layer. BRANZFIRE is able to calculate the time to incapacitation due to the following three effects [3]:

1. The toxicity of combustion products.
2. The thermal radiation effects.
3. The smoke obscuration (visibility).

3.1. The toxicity of combustion products

In BRANZFIRE, toxicity of combustion products is evaluated using the fractional effective dose (FED) method thoroughly described in reference [1]. The model evaluates the sum of the FEDs at a specified height for incapacitation due to carbon monoxide, and hypoxia (lack of oxygen) and accounts for the accelerated breathing rate caused by exposure to carbon dioxide. An FED of 1.0 means that an incapacitation end point has been reached.

The model considers the time-dependent exposure of carbon monoxide in the upper layer by calculating a fractional effective dose for incapacitation using Eqs. (1) and (2) for the concentration of carboxy-haemoglobin in the blood.

Table 1 RMV and COHb incapacitation doses for different activity levels [3].

Activity level	RMV_0 (l/min)	COHb incapacitation dose (%)
At rest	8.5	40
Light work	25	30
Heavy work	50	20

$$FED_{CO} = \frac{3.317 * 10^{-5} * RMV}{\%COHb} \int_0^t (ppmCO)^{1.036} dt \quad (1)$$

$$\%COHb = (3.317 * 10^{-5})(ppmCO)^{1.036}(RMV)t \quad (2)$$

RMV is the volume (in litres) of air breathed per minute and varies with the activity level. RMV is adjusted for the accelerated breathing rate caused by excess carbon dioxide as follows:

$$RMV = RMV_0 * \exp(0.2486\%CO_2) \quad (3)$$

An appropriate activity level could be selected from Table 1.

Similarly, the FED for oxygen hypoxia is determined by evaluating the following integral equation [3]:

$$FED_{O2} = \int_0^t \frac{1}{\exp[7.98 - 0.528(20.84\% - O_2\%)]} dt \quad (4)$$

BRANZFIRE allows the user to identify the height within the compartment at which the incapacitation FED will be evaluated. The default height is 1.5 m above the floor, which is a representative 'nose' height for an adult person. The total FED is therefore given by:

$$FED_{tot} = \frac{3.317 * 10^{-5} * RMV}{\%COHb} \int_0^t (ppmCO)^{1.036} dt + \int_0^t \times \frac{1}{\exp[7.98 - 0.528(20.84\% - O_2\%)]} dt \quad (5)$$

BRANZFIRE uses a simple trapezoidal rule to evaluate the integrals using the upper layer species concentrations for the time when the layer interface is below the monitoring height selected by the user, and using the lower layer species concentrations for the time when the layer interface is above the monitoring height. The program only evaluates the integrals when the species concentrations are above initial ambient levels (or below in the case of oxygen).

3.2. The thermal radiation effects

A thermal FED is calculated to account for the cumulative effects of thermal radiation received by a target (at the specified monitoring height above the floor). The radiation incident on the target is assumed to be due to a flat plate source at the layer interface height and at a temperature equal to the upper layer temperature T_u, and with emissivity equal to the upper layer emissivity ε_u. The configuration factor 'ϕ' between the layer interface and the target is calculated for a flat surface and a parallel differential element [3]. The incident radiation is given by:

$$\dot{q}_{rad} = \phi \varepsilon_u \sigma T_u^4 \quad (6)$$

where σ is the Stefan–Boltzmann constant.

The fractional effective dose for thermal radiation is calculated from Eq. (7) for the occupation period specified. The thermal radiation summation is only carried out at those time steps where the incident radiation exceeds an ambient threshold level of 1.7 kW/m^2.

$$FED_{rad} = \int_0^t \frac{1}{55(\dot{q}_{rad} - 1.7)^{-0.8}} dt \quad (7)$$

3.3. The smoke obscuration (visibility)

The mass fraction of soot in the upper layer is given by solving the species generation equations at each time step. This requires a value for the soot yield to be provided by the user. The mass concentration of soot in the upper layer is then given by:

$$C_{soot} = Y_{soot}\rho_u \tag{8}$$

where C_{soot} is the mass concentration of soot in the upper layer (kg soot/m^3); Y_{soot} the mass fraction of soot in the upper layer; and ρ_u the density of the upper layer (kg/m^3).

The average extinction coefficient, k_{avg} (m^{-1}), is given by:

$$k_{avg} = k_m C_{soot} \tag{9}$$

where k_m is the particle extinction cross section (m^2/kg soot) equal to 7600 for flaming combustion.

The maximum distance an observer can recognise an object, usually an exit sign, when viewing the object through smoke is defined as the visibility, 'V'. According to the type of exit sign, the visibility (in metres) is given by:

$$V = \frac{3}{k_{avg}} \quad \text{(for reflective signs)} \tag{10a}$$

$$V = \frac{8}{k_{avg}} \quad \text{(for illuminated signs)} \tag{10b}$$

3.4. The convective heat

The effect of exposure to convective heat is very important hazard of smoke to the occupants of any enclosure in case of fire. The ability to withstand convective heat depends on the gas temperature, moisture content and the exposure time. An empirical relationship between gas temperature and the time to incapacitation is given in Eq. (11).

$$t_{I,conv} = 4.1 \times 10^8 T^{-3.61} \tag{11}$$

where $t_{I,conv}$ is the time (min) to thermal collapse and T (°C) is the temperature at the skin surface.

Thermal tolerance data for unprotected skin of humans suggest a limit of about 120 °C for convective heat, above which considerable pain is quickly incurred along with the production of burns within a few minutes or less.

4. Parametric study using BRANZFIRE

It is suggested by the author of this work to perform a parametric study using BRANZFIRE in order to assess the effect of changing the dimensions of the compartments on the time available for the occupants of these compartments to escape safely to a place of safe refuge. The objective of this study is to attempt to find a suitable relationship between the main dimensions of the compartments and the time at which the condition inside these compartments becomes untenable.

It is suggested to select a realistic design fire scenario that might occur in the accommodation spaces aboard ro-ro/passenger ships. Details of this scenario are as follows:

4.1. Details of the selected fire scenario

4.1.1. The arrangement

It is suggested to select an arrangement of multiple cabins connected to a corridor as shown in Fig. 2.

4.1.2. The fire

The selected fire object for this study is assumed to be located at the centre of the floor of the cabin of fire origin and the fire is assumed to be of the 't^2-medium growth' type. This means that the Heat Release Rate (HRR) rises from zero to 1 MW in 300 s, remains at this level for 600 s, and then decay to zero after a further 300 s. This corresponds to a total HRR of 800 MJ over 1200 s. Fig. 3 shows the (HRR–time) curve of the selected fire.

4.1.3. The vent

There are two vents in this scenario. The two vents are doors that connect the cabin of fire origin and the target cabin to the corridor. Both vents will be assumed open during the entire simulation, and both are assumed to have a width of 1.0 m and a height of 1.9 m.

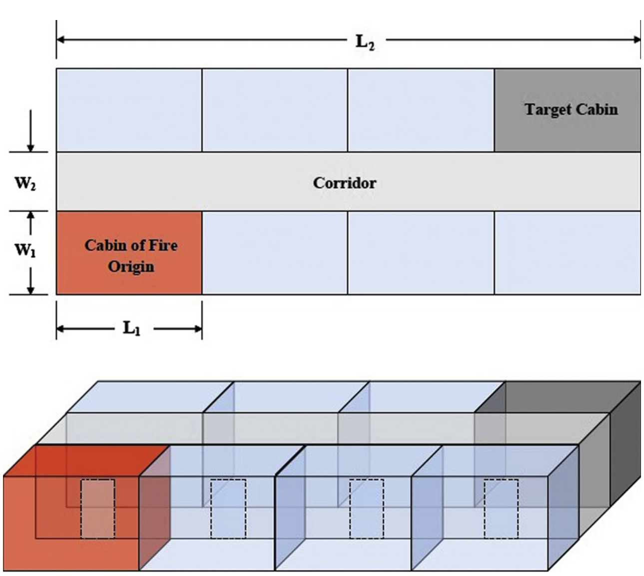

Figure 2 Multiple cabins off a single corridor arrangement.

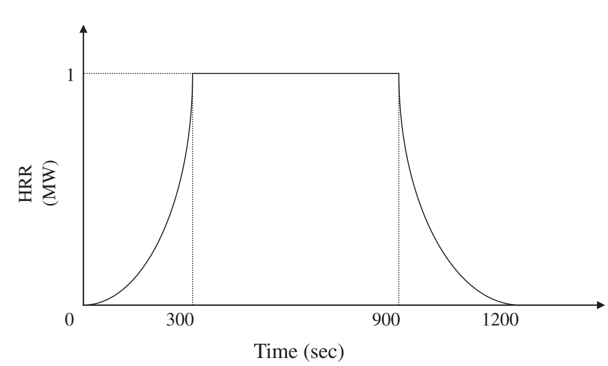

Figure 3 HRR–time curve of the selected fire.

Table 2 The values of the input parameters when the length of the corridor is changed.

Scenario No.	Input parameter					
	Length (m)		Width (m)		Height (m)	
	Cabins	Corridor	Cabins	Corridor	Cabins	Corridor
1	3.00	9.0	4.00	1.80	2.2	2.2
2	3.00	12.0	4.00	1.80	2.2	2.2
3	3.00	15.0	4.00	1.80	2.2	2.2
4	3.00	18.0	4.00	1.80	2.2	2.2
5	3.00	21.0	4.00	1.80	2.2	2.2
6	3.00	24.0	4.00	1.80	2.2	2.2
7	3.00	27.0	4.00	1.80	2.2	2.2
8 (base scenario)	3.00	30.0	4.00	1.80	2.2	2.2
9	3.00	33.0	4.00	1.80	2.2	2.2
10	3.00	36.0	4.00	1.80	2.2	2.2
11	3.00	39.0	4.00	1.80	2.2	2.2
12	3.00	42.0	4.00	1.80	2.2	2.2
13	3.00	45.0	4.00	1.80	2.2	2.2
14	3.00	48.0	4.00	1.80	2.2	2.2
15	3.00	51.0	4.00	1.80	2.2	2.2
16	3.00	54.0	4.00	1.80	2.2	2.2

Table 3 The values of the input parameters when the width of the corridor is changed.

Scenario No.	Input parameter					
	Length (m)		Width (m)		Height (m)	
	Cabins	Corridor	Cabins	Corridor	Cabins	Corridor
17	3.00	30.0	4.00	1.2	2.2	2.2
18	3.00	30.0	4.00	1.4	2.2	2.2
19	3.00	30.0	4.00	1.6	2.2	2.2
8 (Base Scenario)	3.00	30.0	4.00	1.8	2.2	2.2
20	3.00	30.0	4.00	2.0	2.2	2.2
21	3.00	30.0	4.00	2.2	2.2	2.2
22	3.00	30.0	4.00	2.4	2.2	2.2

4.2. Running the fire simulation program

In this study, the main dimensions of the cabins and the connecting corridor have been changed while the dimensions of the vents have kept constant. No changes have been made to the fire load or its location. The linings of walls, floors and ceilings are assumed to be made of steel plates with the following characteristics: thickness of 7 mm, density of 7850 kg/m^3, thermal conductivity of 45.8 W/m K, specific heat of 460 J/kg K, and emissivity of 0.9.

A series of changes in length and width of the corridor as well as the height of both the corridor and the connected cabins has been carried out. The length has been systematically changed from 9.0 to 54.0 m, the width from 1.2 to 2.4 m and the height from 2.0 to 2.5 m.

It should be kept in mind that the effects of smoke and heat on the human behaviour depend on the height above the floor (monitoring height, H^*) at which the toxicity parameters are calculated. Two monitoring heights have been selected to calculate at which the fire toxicity, namely, H^* equals 0.5 m and 1.5 m respectively. At $H^* = 1.5$ m, the occupant is assumed to be standing on the floor, while at $H^* = 0.5$ m the occupant is assumed to be crawling on the floor. These led to 27 different scenarios that need to be simulated in BRANZFIRE. Each scenario has to be simulated twice to calculate the required outputs at the two selected monitoring heights. In all scenarios, the occupants are assumed to have a light work activity level, and that all existing signage is of the reflective type. The planned simulation time is 20 min, which is sufficient for the condition inside the compartments to develop and reach untenable condition, hence impair the evacuation process of their occupants.

Tables 2–4 show the values of these parameters for each scenario. The output results of the simulation program have been tabulated and then plotted. Figs. 4–12 show the output results for the changes in the environment of the cabins and corridor at monitoring heights of 1.5 m and 0.5 m due to changes in length, width and height.

5. Analysis of the results

It is observed from Figs. 4, 7 and 10, at a monitoring height of 1.50 m above the floor of the *cabin of fire origin*, that:

Table 4 The values of the input parameters when the height of the corridor is changed.

Scenario No.	Input parameter					
	Length (m)		Width (m)		Height (m)	
	Cabins	Corridor	Cabins	Corridor	Cabins	Corridor
23	3.00	30.0	4.00	1.8	2.0	2.0
24	3.00	30.0	4.00	1.8	2.1	2.1
8 (Base Scenario)	3.00	30.0	4.00	1.8	2.2	2.2
25	3.00	30.0	4.00	1.8	2.3	2.3
26	3.00	30.0	4.00	1.8	2.4	2.4
27	3.00	30.0	4.00	1.8	2.5	2.5

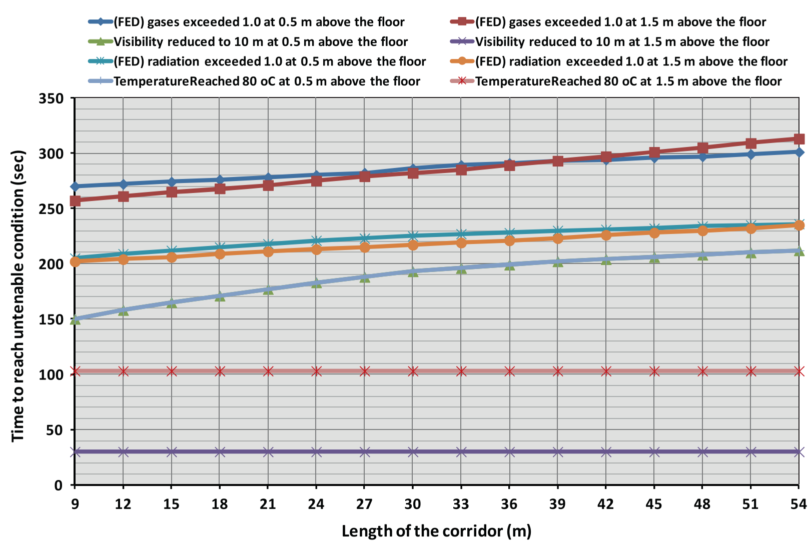

Figure 4 Changes in the time to incapacitation inside the cabin of fire origin with varied length of the corridor at two monitoring heights.

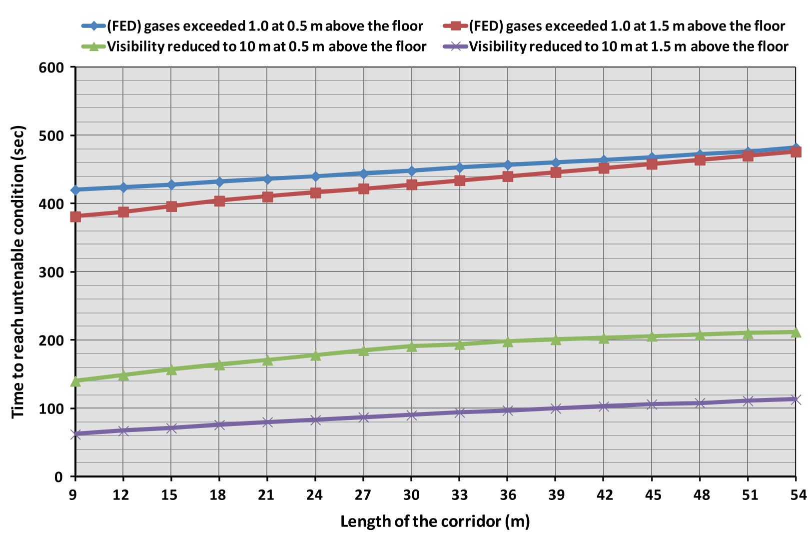

Figure 5 Changes in the time to incapacitation inside the corridor with varied length of the corridor at two monitoring heights.

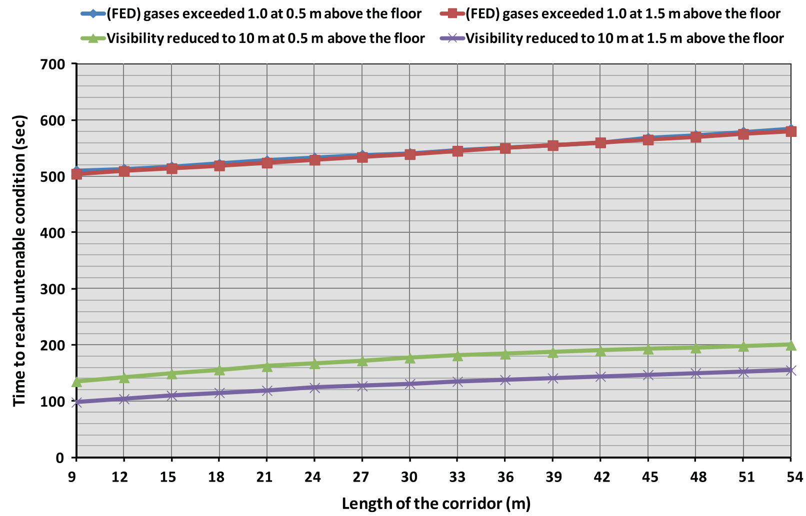

Figure 6 Changes in the time to incapacitation inside the target cabin with varied length of the corridor at two monitoring heights.

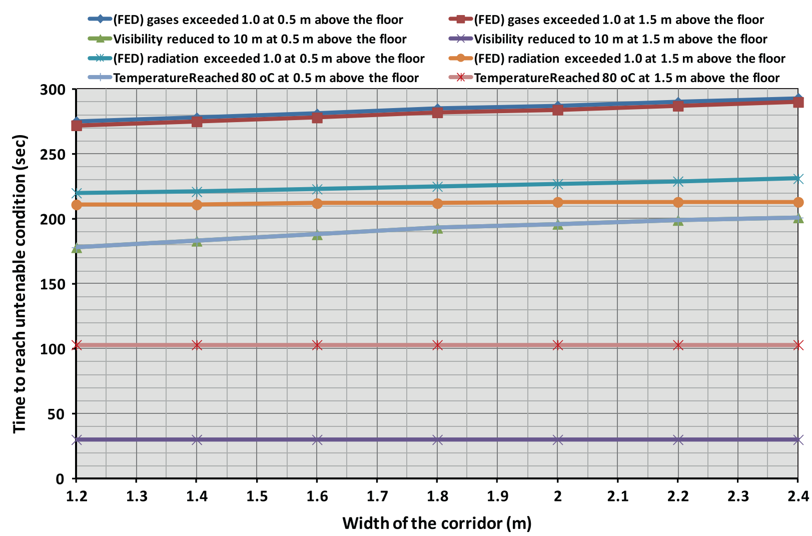

Figure 7 Changes in the time to incapacitation inside the cabin of fire origin with varied width of the corridor at two monitoring heights.

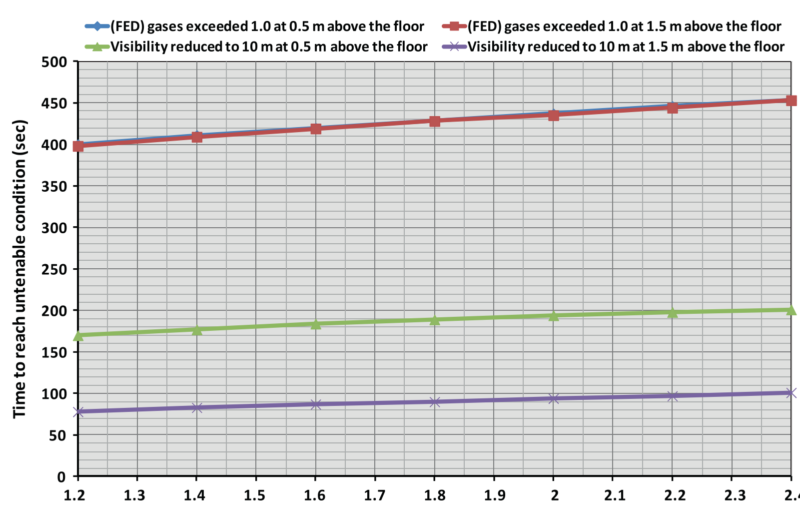

Figure 8 Changes in the time to incapacitation inside the corridor with varied width of the corridor at two monitoring heights.

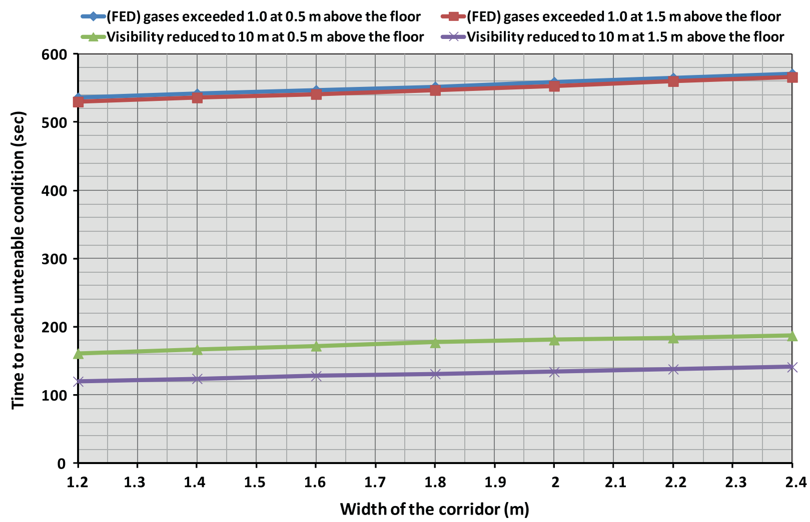

Figure 9 Changes in the time to incapacitation inside the target cabin with varied width of the corridor at two monitoring heights.

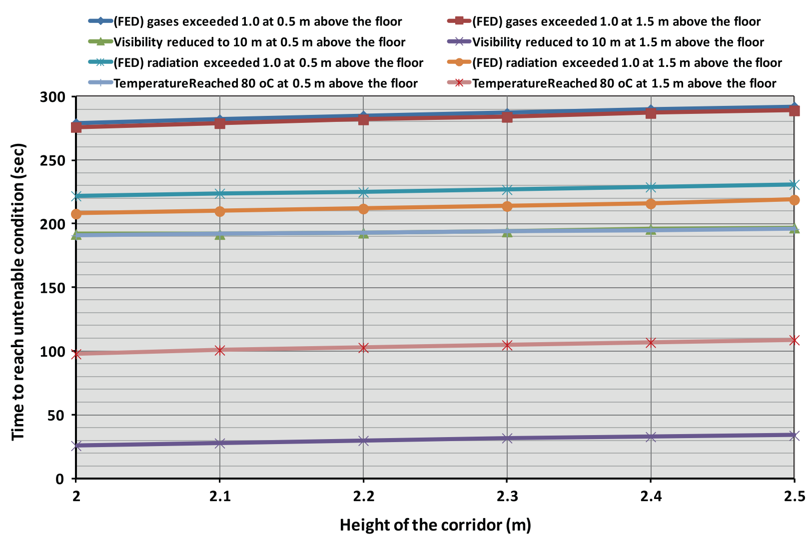

Figure 10 Changes in the time to incapacitation inside the cabin of fire origin with varied height of the corridor at two monitoring heights.

- Regardless the dimensions of the corridor, the tenability criterion that firstly affects the time to reach untenable condition inside the cabin of fire origin is the smoke obscuration criterion (i.e., reduction in visibility).
- Both convective heat (i.e., temperature reaches untenable value of 80 °C) and smoke obscuration criteria remain constant with varying length and width, while increase linearly with increasing height of the corridor.
- The FED_{gases} criterion increases linearly with increasing the three parameters of the corridor.
- The FED_{rad} criterion slightly increases with increasing length and height of the corridor, while nearly remains constant with varying width of the corridor.

It is observed also from Figs. 4, 7 and 10, but at a monitoring height of 0.50 m above the floor of the *cabin of fire origin*, that:

- In spite of the varying dimensions of the corridor, both smoke obscuration and convective heat tenability criteria occur at the same time and are firstly affect the time to reach untenable condition inside the cabin of fire origin.
- Both FED_{gases}, and FED_{rad} criteria increase linearly with increasing the three dimensions of the corridor.

From Figs. 5, 8 and 11 and at monitoring heights of 1.50 m and 0.50 m above the floor of the *corridor*, it is clear that:

- The smoke obscuration criterion is the tenability criterion that first reaches its critical value and affects the time to reach untenable condition inside the corridor.
- The FED_{gases} criterion has nearly the same value at both monitoring heights (except with varying length of the corridor) and increases linearly with increasing the three dimensions of the corridor.

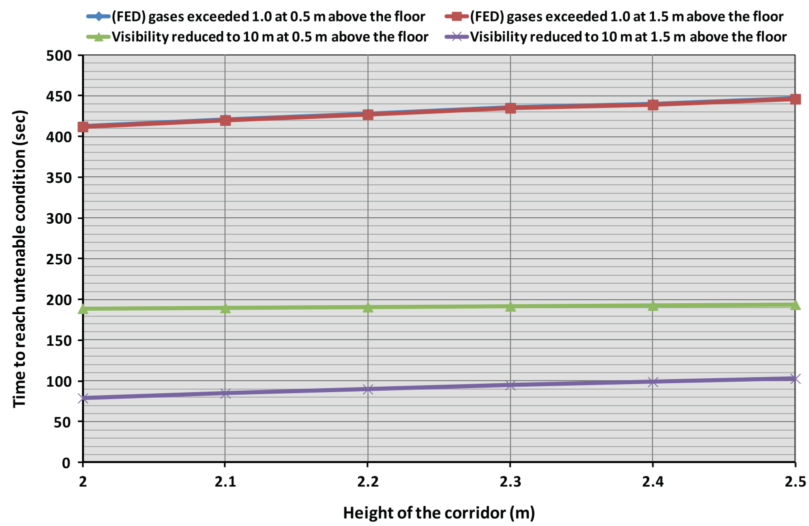

Figure 11 Changes in the time to incapacitation inside the corridor with varied height of the corridor at two monitoring heights.

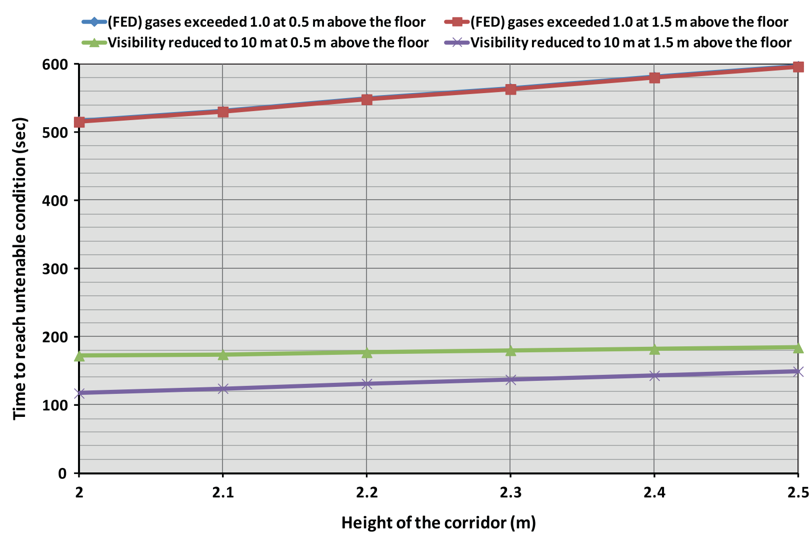

Figure 12 Changes in the time to incapacitation inside the target cabin with varied height of the corridor at two monitoring heights.

- Both convective heat and FED_{rad} criteria never reached until the end of the simulation time indicating that they have no effect on the time to reach untenable condition inside the corridor.

From Figs. 6, 9 and 12 one can observe, at both monitoring heights of 1.50 m and 0.50 m above the floor of the *target cabin*, that:

- The smoke obscuration criterion is the first tenability criterion that affects the time to reach untenable condition inside the target cabin.
- The FED_{gases} criterion has nearly the same value at both monitoring heights and increases linearly with increasing the three dimensions of the target cabin.
- Both convective heat and FED_{rad} criteria never reached until the end of the simulation time indicating that they have no effect on the time to reach untenable condition inside the target cabin.

6. Concluding remarks

It is obvious from the results of this parametric study that the most important tenability criterion that would affect the tenability condition inside the compartments, in case of fire, and regardless the dimensions of the corridor, is the visibility criterion.

The tenability criteria that come next in importance after the visibility are convective heat, FED_{rad}, and FED_{gases} respectively.

Both the convective heat and FED_{rad} criteria only reach their critical values inside the cabin of fire origin and have no effects on the condition inside both the corridor and the target cabin.

All predicted criteria showed linear relationship with the varied dimensions of the corridor at both monitoring heights, except for the convective heat and visibility criteria, where they showed nonlinear variation with both length and width of the corridor at a monitoring height of 0.50 m above the floor of the cabin of fire origin.

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